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Fracture Surface Area Effects on Fluid Extraction and the Electrical Resistivity of Geothermal Reservoir Rocks

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FRACTURE SURFACE AREA EFFECTS ON FLUID EXTRACTION AND THE ELECTRICAL RESISTIVITY OF GEOTHERMAL RESERVOIR ROCKS

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ABSTRACT

Laboratory measurements of the electrical resistivity of fractured analogue geothermal reservoir rocks were performed to investigate the resistivity contrast caused by active boiling and to determine the effects of variable fracture dimensions and surface area on water extraction. Experiments were performed at confining pressures up to 10 MPa (100 bars) and temperatures to 170°C. Fractured samples show a larger resistivity change at the onset of boiling than intact samples. Monitoring the resistivity of fractured samples as they equilibrate to imposed pressure and temperature conditions provides an estimate of fluid migration into and out of the matrix. Measurements presented are an important step toward using field electrical methods to quantitatively search for fractures, infer saturation, and track fluid migration in geothermal reservoirs.

INTRODUCTION AND BACKGROUND

Rock electrical properties are sensitive to factors such as the nature and amount of pore saturant, temperature, and pressure (Llera et al., 1990), surface conduction, and microstructural properties such as porosity of the rock matrix. The amount of the pore saturant and its nature (i.e., whether it is liquid water, other fluids, steam, and other gases) and microstructural properties are the most significant factors. Most dry rocks are excellent insulators in vacuo, but saturation with distilled water decreases resistivity by 8 orders of magnitude and more (Duba et al., 1978). In water-saturated rocks, increasing temperature from 25 to 250¡C decreases the electrical resistivity by about an order of magnitude (Llera et al., 1990).

The electrical properties of geothermal rocks are important for numerous reasons including understanding field wide properties, such as defining the field boundaries, following the effects of production including formation of a steam cap, and tracking injectate. Electrical methods provide the best means to detect and follow fluid movement in the subsurface and evaluating the mass in place in a fluid-dominated geothermal field (Murray et al., 1995). However, effective use of field electrical results requires connecting electrical response to underlying physical processes. Laboratory experimental measurements of carefully characterized materials under controlled conditions provide the means to accomplish this.

Previous electrical measurements on intact samples from The Geysers (Roberts et al., 2001a; 2001b) and Awibengkok (Roberts et al., 2000), indicate boiling phenomena attributed to vapor-pressure lowering. As the properties of fractures play a large role in the performance of geothermal reservoirs, in this paper we report electrical resistivity measurements on samples with prepared artificial fractures in order to assess the electrical signatures which would be indicative of fluid- and steam-filled fractures in situ. Geophysical electrical methods rely on contrast in resistivity to locate fractures and to determine if steam is present. These methods include the long-spacing induction tool, cross-well EM and electrical resistance tomography (ERT).

Here we present preliminary measurements of the electrical resistivity of samples in which fluid is extracted from the matrix by manipulating the pore pressure and volume of the pore pressure control system. These measurements show the transient resistivity response caused by the movement of a boiling front into the rock matrix. These

measurements show promise for evaluating the time dependence of fracture-matrix interaction during reservoir production.

EXPERIMENTAL PROCEDURE

Experimental Apparatus

The apparatus consists of an externally heated pressure vessel with separate pumps and controls for confining pressure and pore pressure on either side of the sample (Figure. 1). A complete description of the experimental apparatus and measuring procedures is reported by Roberts et al. (2001a). Pore pressure was controlled independently between 0 and 5.0 MPa, and for convenience the two systems are referred to as up- and down-stream pressure systems. An impedance bridge was used to measure the resistance of the electrically isolated samples at 1 kHz. Electrical resistivity was calculated from the resistance and geometry of the core. Temperature was measured with type T thermocouples with an accuracy of –2¡C. Resistivity measurements have been made at temperatures up to 275°C. Data collection was automated by use of a scanning unit and microcomputer.

Samples and Preparation

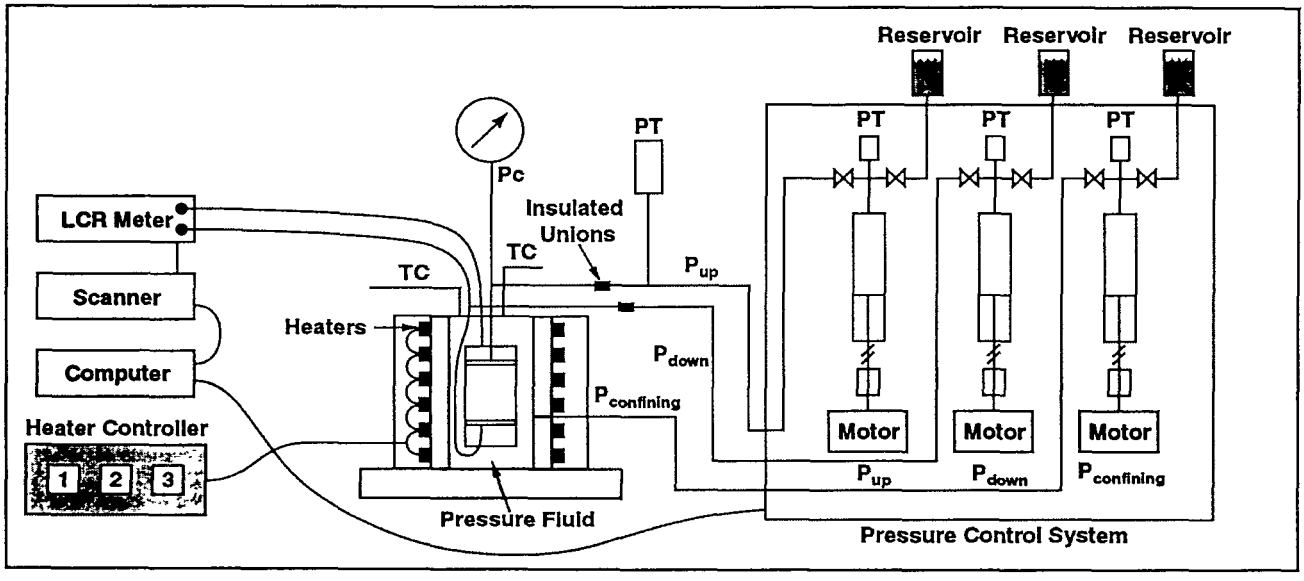

Figure 1. Schematic of apparatus. Sample is electrically isolated and held in an externally heated pressure vessel with separate reservoirs, pumps, and controls for confining and pore pressure. Type J thermocouples measure temperature of the three-zone heater and at two locations adjacent to the sample. An impedance bridge (LCR meter, HP4284a) is used to measure the electrical properties of the sample. A microcomputer controls the experiment and data collection. A second set of pore pressure pumps (not shown) permit accurate determination of flow rate through samples.

Table 1. Experimental Samples

Name	Comment	Diameter, cm	Length, cm	Slot width, cm	slot depth, cm	Slot volume, cm^3	Porosity #
Ts_5	medium	2.540	2.505	0.965	0.050	0.121	0.010
Ts_6	small	2.540	2.510	0.450	0.050	0.056	0.082
Ts_7	large	2.540	2.510	1.905	0.050	0.239	0.091
Ts_1	tpt1gs1	2.540	2.540	1.880	0.050	0.239	0.120
Tnf	Natural fracture	2.470	2.540	2.470	0.0076	0.048	0.108
Ts_2	small	2.518	2.516	0.467	0.048	0.056	0.120
Ts_3**	large	2.538	2.570	1.893	0.050	0.242	0.120
Ts_4**	medium	2.525	2.513	0.942	0.047	0.112	0.120
A4506	Awibengkok intact	2.532	2.030				0.030
A4506_s	Awibengkok slotted	2.532	2.030	1.902	0.050	0.192	0.030
Ts_4a	medium	2.534	2.539	0.944	0.049	0.118	nd
Ts_3a	large	2.522	2.538	1.893	0.048	0.231	nd
A3034	Awibengkok intact	2.530	2.032				0.140
A3034_s	Awibengkok slotted	2.512	2.009	1.905	0.036	0.136	0.140

** Indicates run failed
# Matrix porosity
nd not determined

Samples were prepared by machining right-circular cylinders approximately 2.0 to 2.6 cm high and 2.5°cm diameter. Table 1 lists parameters for samples prepared for this study including samples not yet used in experiments and unsuccessfully run samples. The primary reason for an experimental failure is leakage or rupture of the jacket. Porosity was determined by mercury injection porosimetry or by subtracting dry density from wet density. Samples were saturated with a pore fluid prepared from high-purity salts and distilled water by taking samples dried under vacuum at 35¡C and back-filling with the NaCl solution. Samples were then left immersed in the solution for several days until the weights were nearly constant. Some slight increases in weight with time occurred but do not affect reported porosities by more than 10%. All samples were saturated with a mixture of 1.65 g NaCl per liter of water. The fluid was boiled for one hour before being used for saturating the samples to remove dissolved gases. Submerged samples were also pumped under rough vacuum for about 1 hour for more complete saturation and gas removal. Fluid resistivity at room temperature was ~6.4 ‰-m (conductivity = 1.53 mS/cm). The sample assembly used in this study is shown in Figure 2.

Cylindrical samples containing artificial fractures were prepared by cutting the samples in half lengthwise and regrinding the two halves to a cylindrical shape. The fractures were created by grinding slots the entire length of one half of the sample. The dimensions of the slot are ~0.5 mm deep, 25 mm long, and width varied between 4.5 and 19 mm. The volume of the slots ranged from 0.06 to 0.24 cm^3 and the total volume of the sample is ~12.5 cm^3. The slot was supported by ridges of rock left in place at the edges of the sample so that the slots remained open during experiments. The two halves were ground flat and when mated, only the slot permitted the free passage of fluid.

One sample (Tnf) contained a natural fracture. A section of core containing a partially healed fracture was located and recored to 2.5 cm diameter. This was done so the fracture was approximately parallel to the axis of the cylinder. During the coring process the two halves of the sample separated. When remated, small gold shims approximately 1 mm square and 76 micron thick (0.003 inches) were placed on either end of the sample to maintain an open fracture.

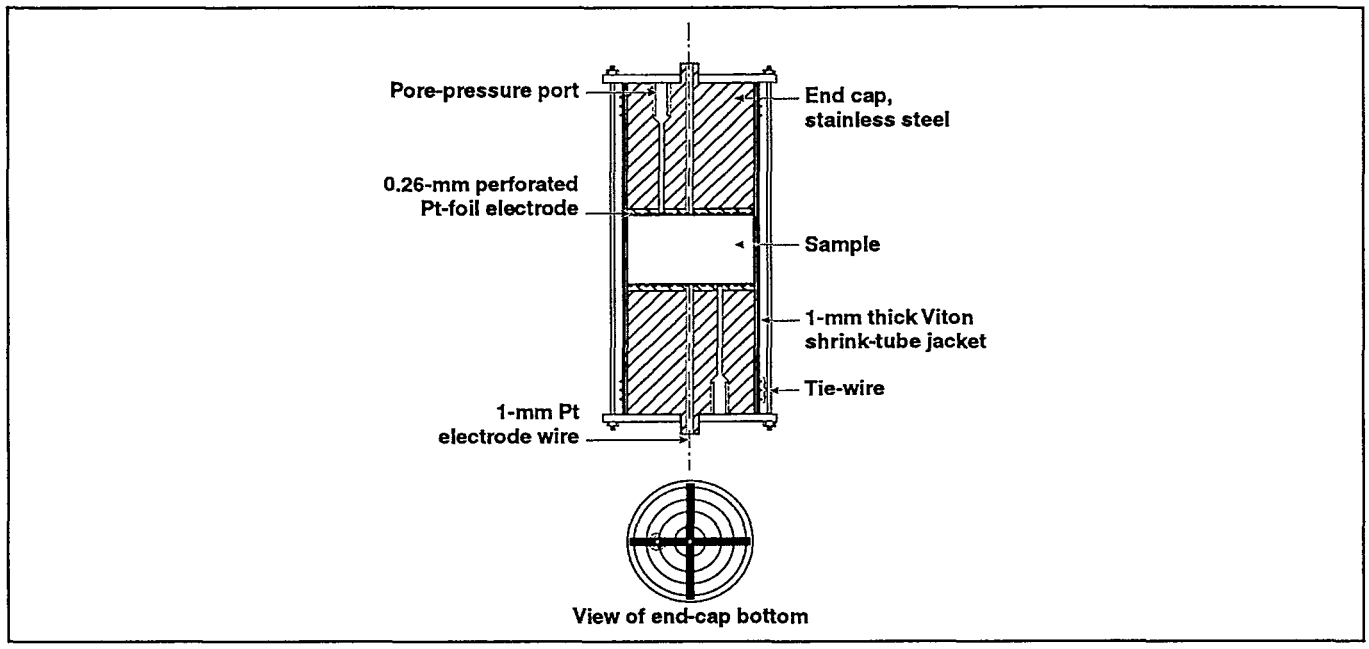

Figure 2. Schematic of sample assembly showing perforated endcaps, electrodes, jacket material, pore pressure inlets, and frame.

ELECTRICAL RESISTIVITY RESULTS AND DISCUSSION

Effects of Fractures on Resistivity

Resistivity as a function of pore pressure for samples Ts_5, Ts_6, and Tnf is shown in Figure 3. The confining pressure was held constant while the pore pressure varied. For these experiments the confining pressure was 3.5 MPa. These starting pressures are such that the beginning confining pressure:pore pressure ratios are approximately 2:1. Lowering the pore pressure results in a gradual increase in resistivity followed by a sharp jump in resistance when the pressure is lowered to that where bulk water transitions to steam (Roberts et al., 2001a). For rocks containing a synthetic or natural fracture, the jump in resistivity at this transition is much higher than for intact samples. One goal of this study is to determine the influence of fracture surface area on changing electrical resistivity after the fluid begins to boil. Figure 3 shows this for three samples, two with prepared fractures (Ts_5 and Ts_6) and one rock with a natural fracture (Tnf).

Tnf is more conductive than either Ts_5 or Ts_6 even though it is at lower temperature and the fracture volume is lower than the slotted samples. A possible reason is that the fracture is partially mineralized and has a higher surface conduction component. Weathering on the fracture surface could also cause enhanced surface conductivity over the fresh surfaces of the samples with prepared fractures. The relative magnitude of the resistivity increase with boiling is larger for Tnf than for the other samples even though the aperture is smaller. One reason for this could be that the natural fracture has a greater surface area than the prepared fracture samples. Also note that sample Tnf was left in the boiling state longer than the other samples.

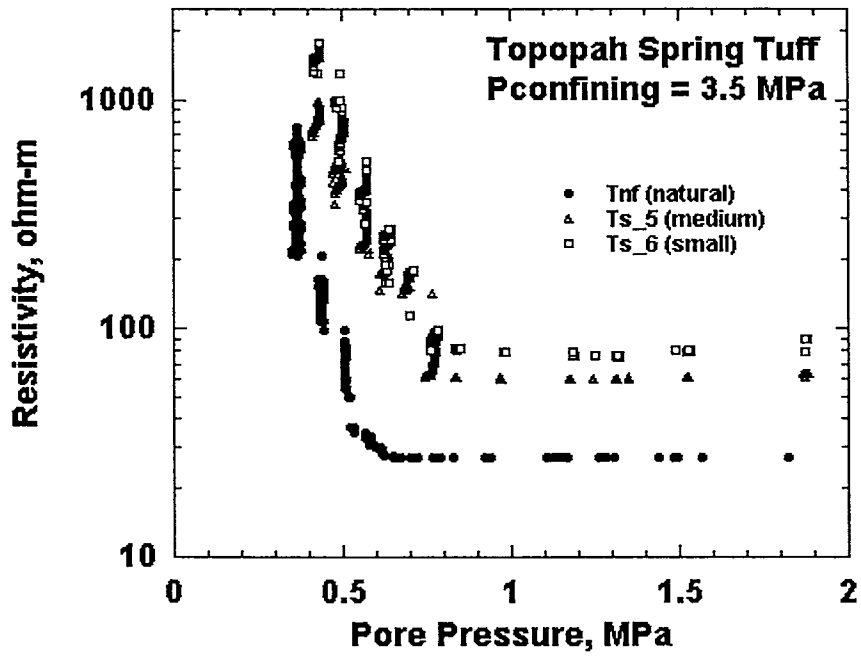

Figure 3. Resistivity vs pore pressure for tuff samples. Confining pressure was held constant while the pore pressure was lowered. The temperature of runs Ts_5 and Ts_6 was 166°C and the temperature of run Tnf was 157°C. The boiling pressure for water is approximately 0.72 MPa and 0.58 MPa for 166 and 157°C, respectively (Haas, 1971). The increasing resistivity at low pressure is attributed to time dependent loss of liquid water from the matrix to the fracture.

Resistance is plotted as a function of time for sample Ts_5, Ts_6, and Tnf (Figure 4). These data are from a second experiment on the same samples (as shown in Fig. 3) where pore pressure was lowered in a large step to below the water-vapor transition. Ts_6 is the smallest slot size and Ts_5 is the middle slot size (Table 1). At time zero the pore pressure was lowered to well below boiling for all the samples, approximately 0.56 MPa for Ts_5 and Ts_6 and 0.37 MPa for Tnf. The same data is plotted in Figure 5 except the time axis is the square root of the elapsed time in seconds. The sample with the smallest slot dimensions is more resistive than the sample with the larger slot dimensions, as expected. The sample with the natural fracture is more conductive than either of the other two samples.

At the temperature of the experiment, we expect the fluid resistivity to be about 0.27 ohm-m as calculated using the exponential relationship from Keller (1966). Taking into account the slot dimensions for the small, medium, and large slots, this corresponds to a resistance of ~ 3012, 1400, or 700 ohm in parallel with the entire sample when the slot is liquid filled. The liquid filled matrix resistance at these conditions is estimated to be ~9200 ohm (Roberts, 2001). Flashing the liquid in the slot or fracture to steam effectively cuts off this conduction pathway causing the rapid increase in resistance seen in Figures 4 and 5. We assume the increase in resistance at longer times is caused by loss of liquid water in the matrix. What is unexpected is the observation that the smaller slot sample remains more resistive than the medium slot sample and the slope is greater when resistance is plotted as a function of the square root of time (Fig. 5). Additional experiments are planned to confirm this result. Possible causes include heterogeneities specific to the samples selected, loss of liquid water to the fracture which conducts better than expected (surface conductance), and phenomena related to changing ionic concentrations of the remaining liquid water. Additional experiments will address these issues.

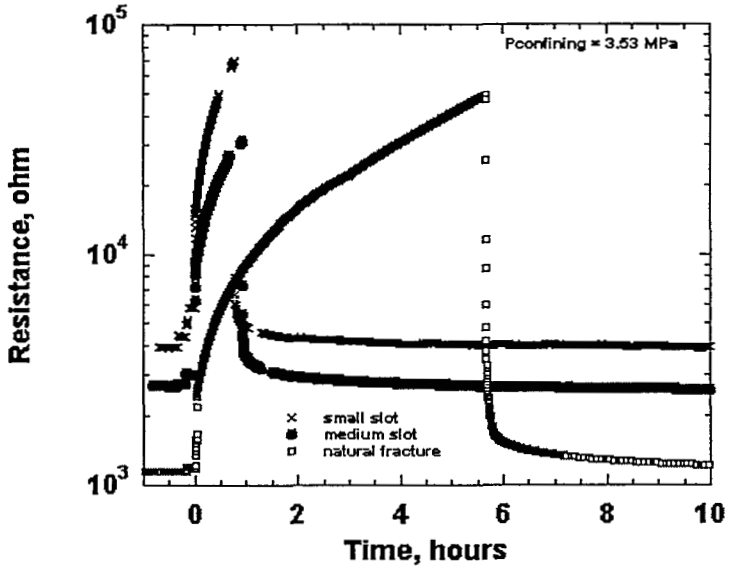

Figure 4. Resistance vs time for three fractured tuff samples. Confining pressure was held constant at 3.5 MPa while the pore pressure was lowered. The temperature of runs Ts_5 (medium slot) and Ts_6(small slot) was 166°C and the temperature of run Tnf (natural fracture) was 157°C.

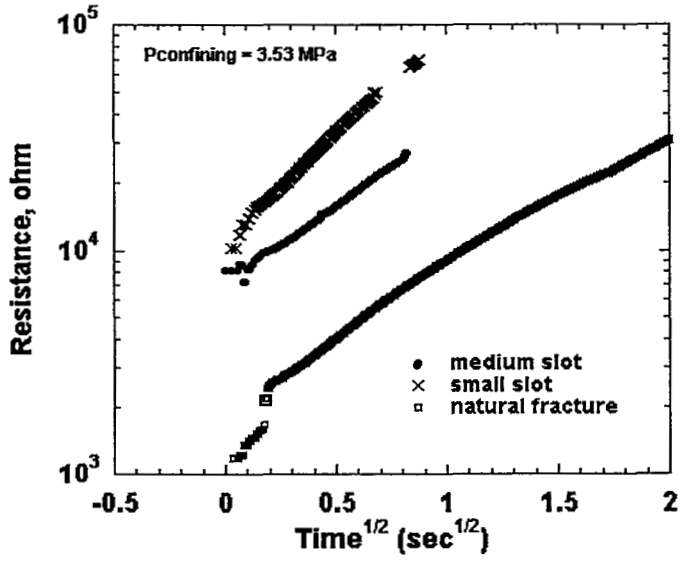

Figure 5. Resistance vs square root time for three fractured tuff samples.

TRANSIENT RESPONSE OF PORE PRESSURE AND RESISTIVITY

To investigate the transient response of pore pressure and resistivity, we conducted two pressure pulse experiments above and below the boiling point. With the sample at steady-state pore-pressure and resistivity, we lowered the pore pressure for approximately 5 seconds and then isolated the sample from the pump controlling pore-pressure so

that the remainder of the experiment was at a constant volume condition. This created a pressure gradient within the sample because 5 seconds was a sufficient time period to establish a uniform lower pressure in the slot, but insufficient to allow the fluid in the matrix to reach equilibrium at the reduced pressure. The pressure in the slot began to rise due to diffusion of the pressure gradient in the sealed sample as fluid leaves the matrix and enters the slot until the pressure gradient disappears.

Prior to initiating these experiments, we set the sample pore pressure to 1.72 MPa (250 psia) for 24 hours to allow the pressure in the sample to equilibrate to the set pressure. We then lowered the pore pressure to ~1.03 MPa (150 psi) and after ~5 seconds isolated the sample from the controlling pump. In this case the pore pressure drop was not sufficient to cause boiling. Figure 6 shows measurements of pore pressure and resistivity made during this experiment. As expected, the pore pressure, which, due to its hydraulic connection to the slot is essentially a measure of the slot pressure, increased as the pressure gradient in the matrix diffused. Due to the resulting fluid movement from high to low pressure, the final steady state pore pressure was larger than the initially set pore-pressure. The sample approached steady pressure after about 10 minutes. The decrease in matrix pore pressure resulted in a mild drop in resistivity.

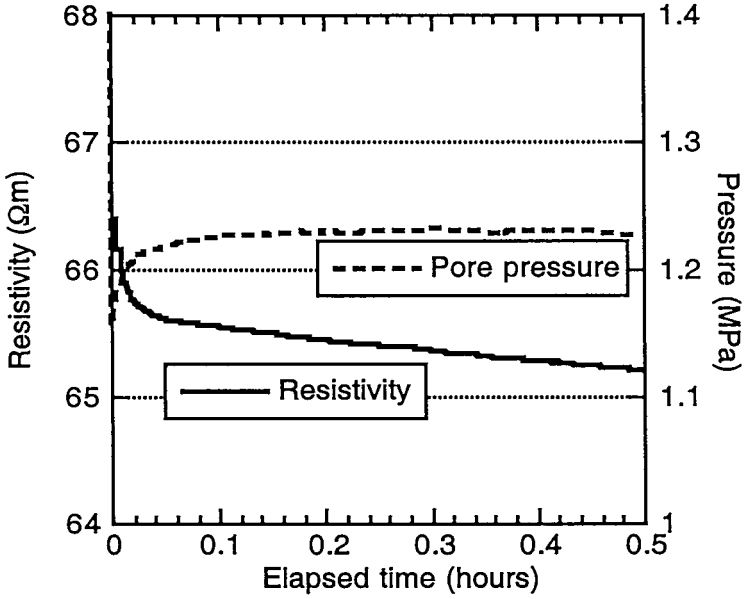

Figure 6. Pressure and resistivity response after lowering pore pressure from 1.82 to 1.15 MPa (above the boiling pressure) immediately followed by halting flow from the sample.

For the second experiment, we lowered the pore pressure from ~1.03 MPa (150 psi) to ~0.34 MPa (50 psi) and after ~5 seconds isolated the sample from the controlling pump. Because 0.34 MPa is well below the phase transition pressure (~0.69 MPa) for the temperature of the experiment (~165°C) the fluid in the slot immediately flashed to steam resulting in a dramatic increase in resistivity (Figure 7). As pressures dropped in the matrix, it is likely that a two-phase (liquid/vapor) zone developed in the matrix as predicted by the heterogeneous boiling model (e.g., Roberts et al., 2001a). Due to the more tortuous flow paths in the two-phase system and the complex interaction of the two phases at the pore scale, the time scale required for the pore pressure to approach equilibrium was considerably longer (~16 hours) than in the saturated experiment. A surprising result is steady increase in resistivity as the pore pressure increased above the phase transition pressure. Above a pressure of ~0.69 MPa, the vapor should return to a liquid state, which would result in the sample resistivity dropping to values that are representative of the saturated sample (i.e., < 10,000 Ωm). However, during this experiment, the resistivity increased to values an order of magnitude greater than those observed in the saturated sample. These results suggest that the slot remained at least partially vapor or gas filled even after the pressure climbed into the liquid region.

These experiments demonstrate the need for including the role of the transient response of pore pressure and resistivity when interpreting electrical measurements of fractured geothermal rocks at reservoir conditions. These

results suggest that the combined interpretation of resistivity and pressure data may provide a means to monitor single and two-phase fluid movement in situ.

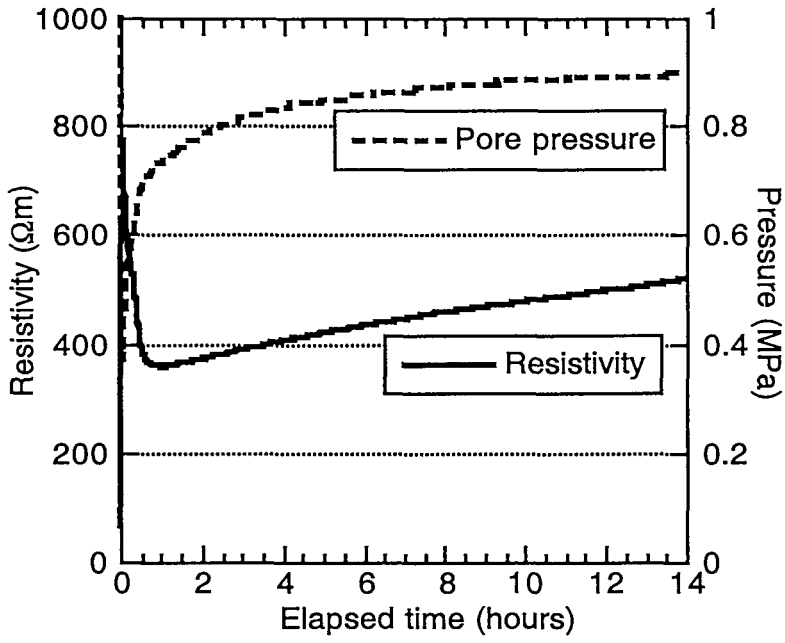

Figure 7. Pressure and resistivity response after lowering pore pressure from 1.21 to 0.39 MPa (below the boiling pressure) immediately followed by halting flow from the sample..

CONCLUSIONS

Resistivity of intact and fractured rocks is sensitive to temperature, composition and state of the pore fluid, and lithology. Measurements presented are an important step toward making the search for fractures using electrical methods quantitative.

After steam is produced in the fractured samples by lowering the pore pressure, the increase in resistance caused by replacing (in part) conducting brine with insulating water vapor is abrupt followed by a gradual increase in resistivity as liquid water is removed from the matrix. The observations are consistent with the heterogeneous boiling model, which occurs because vapor-pressure lowering and adsorption in fine pores maintains fluid in the liquid state across the phase boundary for bulk brine. The characteristic equilibration times for pressure and resistivity are similar and much longer for the saturated case. Relative permeability appears to control both processes.

Experimental results for rocks with synthetic propped fractures reinforce the idea that electrical measurements provide a means for fracture detection. For the samples studied the relationship between resistivity change with decreasing pore pressure and fracture surface area is unclear and requires further study.

New experiments investigating the transient change in resistivity simultaneous with changing pore pressure conditions indicate a complicated system that might be understood through resistivity and relative permeability modelling. These experiments demonstrate the need for including the role of the transient response of pore pressure and resistivity when interpreting electrical measurements of fractured rocks under geothermal reservoir conditions. Results suggest that the combined interpretation of resistivity and pressure data may provide a means to monitor fluid movements for single and two phase fluids in-situ.

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